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An Introduction to the concept of Radioactive Decay and Radioactivity in Nuclear Chemistry

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Introduction

Radioactivity, a term used to describe the emission of radiation or particles through the spontaneous nuclear transformation or disintegration of the atomic nuclei of radioactive molecules was first discovered by Becquerel, a French Scientist in 1896, while he was studying a number of fluorescent and phosphorescent materials to see if they give off Roentgen's radiation. However, he didn't observe fluorescence or phosphorescence from the materials he was studying but a different penetrating radiation was found which do not depend on whether the salt phosphoresced (James 2007). The radiation emitted by the material was spontaneous, apparently undiminished and could discharge an electroscope just like X rays. For his discovery, he received the 1903 noble prize in physics.

Radioactivity can be categorized chiefly according to their nuclear energetics into; alpha-decay, beta-decay, gamma-ray emission, internal conversion, electron capture and positron decay. The fascinating fact about the nuclear radiation is its ability to also release radiation belonging to the electromagnetic spectrum such as the gamma, and X – radiation. Other interesting types of radiation in addition to the electromagnetic and particle radiation are the cosmic radiation and the gravitation radiation which are categorized mostly by their wave nature.

In general, radiations are viewed in a sphere of either having enough energy to cause ionization of atoms of not having enough energy to ionize atoms. Ionizing radiations are usually harmful to living cells which can result in a damage of some useful proteins or important tissues in a living system. Ionizing radiations typically have an energy of over 10eV which is enough energy to take out an electron from an atom thereby producing an ion.

This paper will review important sources of radioactive decay in details and explain some important facts and terms used to determine and characterize radiation, radiative materials and kinetics of radioactive decay.

Radioactive Decay

Radioactive decay is a spontaneous nuclear transformation that has been shown to be unaffected by pressure, temperature, chemical form, etc (except a few very special cases). This insensitivity to extranuclear conditions allows us to characterize radioactive nuclei by their decay period and their mode and energy of decay without regard to their physical or chemical condition (Gregory 2013). Radioactive decay is a property exhibited by atoms of larger atomic number with less nuclear stability. In atoms of smaller atomic number little to no radioactive decay is observed while atoms with an even numbered protons and/or neutrons have generally shown a degree of stability compared to atoms with odd numbers of protons/neutrons. Radioactive decay occurs as an attempt made by unstable radionuclides become stable by a spontaneous nuclear transformation from one nuclear specie to another with a different mass number of atomic number or both. The quantum state of the original radionuclide undergoes transition into another quantum state. The decay energy which appears in the form of an electromagnetic radiation is the energy difference between the two quantum levels in respective transitions.

The rate of decay or transformation of a radionuclide can be described using its activity. The unit of activity is the becquerel (Bq), disintegration per unit second, $1Bq=1s^{-1}$. The activity is a measure of the number of atoms that decay per unit, meaning it gives information about the number of atoms that undergo radioactive decay in each second of the clock. The traditional unit of activity is Curie (Ci), which was originally ascribed to 1g ^{216}Ra (James 2007). The relationship between Curie and Becquerel can be given as; $1Ci = 3.7 \times 10^{10}Bq$.

Kinetics of radioactive decay

As mentioned earlier, the rate of radioactive decay in a given sample is independent of pressure, temperature or any other rate limiting factor commonly observed in chemical and physical changes. However, the rate of decay in a given time interval decreases exponentially with time.

Nuclear decay, which is an irreversible transformation of unstable radioactive nuclide have a direct influence by time and thus, the decay rate is an important way of identifying different radionuclides. It is difficult to predict the radionuclide that will undergo decay because it a completely random event fully dependent on time. As such we only determine the amount of radionuclide that will remain after disintegration.

The equation below gives the number of radioactive nuclei present at time t:

$$N = N_0 e^{-\lambda t}$$

$\mathbf{N_0}$ is the initial amount of the radioactive particles

N is total amount of the radioactive particles after time, **t**
t is the time required for get N
λ is the decay constant

Hence, the kinetics of radioactive decay is concerned with measuring the rates at which a radioactive decay occurs and also probing into the factors that can affect the rate of the disintegration of these atoms.

Half Life

The time dependence of radioactive decay is expressed in terms of the half-life (t½), which is the time required for one-half of the radioactive atoms in a sample to undergo decay (Gregory 2013). The half-life can also be said to be the time for the radioactivity of a sample to be decreased to half its value. This means that, when the supposedly determined half-life of a radioactive sample is reached, the radioactive intensity will be half the value it previously exhibited. Half-lives vary from millions of years to fractions of seconds (Gregory 2013). Simple laboratory techniques can be used to experimentally determine the half-lives of samples with a much longer half-lives, whereas shorter half-lives require a more complex technique.

The half-life of a radioactive decay is the time required for half the radioactive atom to disintegrate completely. The most commonly known application of half-life is ^{14}C dating. Carbon-14 as shown on table 1 below has a half-life of about 5700 years and it is a reliable information utilized in describing or measure the age of organic materials.

William Libby developed the process of carbon-14 dating which was basically on the fact that carbon is constantly made in the atmosphere and incorporated through plants by photosynthesis then to the animals when they ingest these plants. The process of carbon cycle can be regarded as the process of life and that's why most living matter are composed of carbon. Once a plant or an animal dies, carbon-14 undergoes decay thereby providing valuable information about the age of the animal or plant from a measured amount of the carbon-14 in a sample.
The equation below is the mathematical expression used to describe the half-life of a radioactive particle:

$$(1) \quad N(t) = N_0 \left(\frac{1}{2}\right)^{\frac{t}{t_{\frac{1}{2}}}}$$

$$(2) \quad N(t) = N_0 e^{-\frac{t}{\tau}}$$

$$(3) \quad N(t) = N_0 e^{-\lambda t}$$

(4) $t_{1/2} = \tau \ln 2 = \ln 2 / \lambda \quad (\tau = 1/\lambda)$

Where;

N_0 is the initial amount of the radioactive particles

N_t is total amount of the radioactive particles after time, **t**

$t_{1/2}$ is the half-life

τ is the mean lifetime

λ is the decay constant

Table 1 gives several examples of radioactive materials and Isotopes with the type of decay they exhibit and their respective half-lives. Different radioactive materials have different half-lives which varies from millions of years to very few seconds.

Table 1: Selected radioactive isotopes

Isotope	**Half-Life**	**Principal Radiations (type, MeV, frequency)**
Neutron	614 s	β–, 0.782 (100%)
Tritium (H-3)	12.32 y	β–, 0.01859 (100%)
Carbon-14	5700 y	β–, 0.156 (100%)
Nitrogen-13	9.965 m	β +, 1.199 (99.8%); γ, 0.511 (199.6%) [annihilation]
Nitrogen-16	7.13 s	β–, 4.289 (66.2%), 10.42 (28%); γ, 6.129 (67%), 7.115 (4.9%)
Sodium-24	15.0 h	β–, 1.393 (99.9%); γ, 1.369 (100%), 2.754 (99.9%)
Phosphorus-32	14.268 d	β–, 1.711 (100%)
Sulfur-35	87.37 d	β–, 0.167 (100%)
Argon-41	1.827 h	β–, 1.198 (99.2%); γ, 1.294 (99.2%)
Potassium-40	1.248×10^9 y	β–, 1.311 (89.1%); EC γ, 1.461 (10.7%)
Cobalt-60	5.271 y	β–, 0.318 (99.9%); γ, 1.173 (99.85%), 1.332 (99.98%)
Krypton-85	10.76 y	β–, 0.687 (99.6%); γ, 0.514 (0.4%)
Strontium-90	28.79 y	β–, 0.546 (100%)
Yttrium-90	64.0 h	β–, 2.280 (~ 100%)
Molybdenum-99	65.98 h	β–, 0.436 (16.4%), 1.214 (82.2%); γ, 0.740 (12.3%)
Technetium-99m	6.01 h	IT (~ 100%); γ, 0.141 (89%)

Isotope	Half-Life	Principal Radiations (type, MeV, frequency)
Iodine-129	1.57×10^7 y	β–, 0.154 (100%); X, 0.0295 (20%), 0.0298 (37%)
Iodine-131	8.025 d	β–, 0.248 (2.1%), 0.334 (7.2%), 0.606 (89.6%); γ, 0.284 (6.1%), 0.364 (81.5%), 0.637 (7.2%)
Xenon-135	9.14 h	β–, 0.915 (96%); γ, 0.250 (90%)
Cesium-137	30.08 y	β–, 0.514 (94.7%), 1.176 (5.3%); γ, 0.662 (85.1%)
Iridium-192	73.827 d	β–, 0.259 (5.6%), 0.539 (41.4%), 0.675 (48.0%); γ, 0.296 (28.7%), 0.308 (30.0%), 0.317 (82.7%), 0.468 (47.8%); EC (4.9%)
Polonium-210	138.4 d	α, 5.304 (100%)
Radon-222	3.8235 d	α, 5.489 (99.9%); γ, 0.510 (0.08%)
Radium-226	1600 y	α, 4.601 (6.2%), 4.784 (93.8%); γ, 0.186 (3.6%)
Thorium-232	1.405×10^{10} y	α, 3.947 (21.7%), 4.012 (78.2%)
Uranium-235	7.038×10^8 y	α, 4.366 (17%), 4.398 (55%); X, 0.013 (37%); γ, 0.144 (11%), 0.186 (57%)
Uranium-238	4.468×10^9 y	α, 4.151 (21%), 4.198 (79%); X, 0.013 (7%)
Plutonium-238	87.7 y	α, 5.456 (29.0%), 5.499 (70.9%)
Plutonium-239	2.411×10^4 y	α, 5.106 (11.9%), 5.144 (17.1%), 5.157 (70.8%)
Americium-241	432.6 y	α, 5.443 (13.1%), 5.486 (84.8%); γ, 0.0595 (35.9%)
Californium-252	2.645 y	α, 6.076 (15.2%), 6.118 (81.6%); SF (3.1%)

As seen above on table 1, radioactive decay is dependent on the type of particle involved in the decay process. Radioactive decay can be categorized into α, β, and γ- radiation. Alpha-decay is the emission of helium nuclei. Beta-decay is the creation and emission of either electrons or positrons, or the process of electron capture. Gamma-decay is the emission of electromagnetic radiation where the transition occurs between energy levels of the same nucleus (Gregory 2013). Internal conversion is a situation whereby a nucleus loses its energy through interacting with the orbital electrons, leading to an expulsion of an electron from the atom and consequently ionizing the atom.

As mentioned earlier, the target of an atom is to become stable and to attain stability, it is achieved by balancing the nuclear species to minimize coulombic interactions between particles of similar charges (such as the repulsion between the negatively charged electrons or between positively charged protons). This is done by either losing a particle, emission of an electromagnetic radiation or converting a neutron to a proton or vice versa. Another type of radioactive decay is the spontaneous fission. Here, a large or heavy nucleus disintegrates spontaneously into two equal and smaller parts. Spontaneous fission is accompanied by the release of an electromagnetic radiation and neutrons.

Decay Series

Radioactive isotopes like uranium-238 and thorium-232 are still in existence since when they were produced in the universe (billions of years ago). The existence of these naturally occurring radioisotopes is due to their long half-lives (table 1). Products of the decay of these radioisotopes exist in a very long chain of radionuclides formed by the emission of α and β particles.

The chain of this decay process of uranium-238 and thorium-232 is termed the decay series. It usually starts with ^{238}U or ^{232}Th and ends with the most stable ^{208}Pb or ^{206}Pb respectively, for ^{238}U and ^{232}Th. Uranium decay series includes 8α and 6β-decay steps and the radionuclides are related by (4n + 2) in which all the mass numbers of the radionuclides are divided by 4 with a remainder of 2. Thorium decay series however, includes a 6α and 4β-decays while the radionuclides are related by the 4n term. Hence the mass numbers of the radionuclides can be evenly divided by 4.

Alpha Decay

Alpha particles result in extensive ionization in matter due to energy of the particle. The limited range of the alpha radiation can be seen from its mass and high energy of ionization leading to a very short wavelength. Alpha particles are practically not influenced by collision with electrons, since the mass of the electron in contrast with the mass of alpha particles is negligible. However, an alpha particle can collide with a nucleus resulting to a deflection of the alpha particle or the nucleus captures the particle to induce a nuclear reaction. If the particles are allowed to pass into a gas, the electrons released by the ionization can be collected on a positive electrode to produce a pulse or current. Ionization chambers and proportional counters are instruments of this kind, which permit the individual counting of each alpha-particle emitted by a sample. (Gregory 2013). Heavy element usually emits alpha particles with mass number of usually greater than the mass number of lead. However, 8Be can also undergo alpha decay, i.e. daughter and alpha particle are equal (Gregory 2013). Alpha-decay can be generally represented by the equation:

$$\boldsymbol{{}^{A}_{Z}X \;\rightarrow\; {}^{A-4}_{Z-2}X + {}^{4}_{2}He}$$

X indicates any radioactive element while A and Z are mass and atomic numbers of the element.

Beta and Positron decay

The emission of ordinary negative electrons from the nucleus was among the earliest observed radioactive decay phenomena. The inverse process, capture by a nucleus of an electron from its atomic orbital, was not observed until 1938 when Alvarez detected the characteristic **X** rays emitted in the filling of the vacancy left by the captured electron. (Kenneth 1988). The positive electron (positron) was discovered in cosmic rays and 2years after, Joliot-Curies (1934) observed the positron in radioactive decay, which was the first discovery of positron emitted from a radionuclide.

Beta and Positron decay usually referred to as beta-decay differ in terms of their respective charges. Beta (β^-) is a negative beta-particle ($_{-1}^{0}\beta$) or an electron which is spontaneously emitted by a nucleus together with an antineutrino $^{0}_{0}\tilde{\nu}$ during beta-decay. The antineutrino, like its antiparticle the neutrino $^{0}_{0}\nu$, has no charge and little or no mass; they have been detected only in rather elaborate experiments (James 2007). The positron-decay nevertheless, involves the release of a positively charged electron ($^{0}_{1}\beta$) concurrently with the neutrino $^{0}_{0}\nu$. The effect of positron decay has a similar effect with electron capture leaving the mass number A, of the radionuclide unchanged. However, the atomic number M, is changed as shown in the positron decay equation below.

$Positron - decay$ $\qquad$ $\boldsymbol{{}^{A}_{Z}X \;\rightarrow\; {}_{Z-1}{}^{A}X + {}^{0}_{1}\beta + {}^{0}_{0}\nu}$

β^- – decay is weaker than alpha radiation and produces less ion pairs per millilitre. Electrons have a great impact on the direction of a beta-particle thereby causing a zigzag motion of beta particles. Energetic electrons cause ionization and molecular excitation in matter, although the effect is weaker and more difficult to detect than for alpha – particles (Gregory 2013). Beta radiation is characterised by the removal of an electron from a radioactive atom usually as a result of the conversion of a neutron to proton (internal conversion).

$Beta - decay$ $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X + {}^{0}_{-1}\beta + {}^{0}_{0}\tilde{\nu}$

Beta radiation interacts with matter in three different ways:

1. Interaction with electrons ionizes the atom by exciting the electron shell.
2. Interaction with the nuclei results in X-ray which is known as the bremsstrahlung effect.
3. Backscattering

Gamma radiation and Internal conversion

The alpha - and beta - decay may leave the daughter nucleus in an excited state. This excitation energy is removed either by gamma-ray emission or by a process called internal conversion (described in the next section). Transmission resulting in gamma emission leave the atomic number, Z and mass number, A unchanged (James 2007). The product of this transition is called an *Isomer* and the process is known as *Isomeric transition.*

Gamma rays and X rays have similar properties and are distinguished by their origins. X-rays are emitted from the electron shell of an atom when an electron falls back to a lower quantum state. The bremsstrahlung effect occurs when an electron is affected by the nuclear field resulting to a radiation of energy. The energy radiated from the bremsstrahlung effect can either be characterized as an X-radiation or gamma-radiation depending on the energy of the photon. Electrons with Energy > 10MeV striking a substance of high atomic number induce an energetic bremsstrahlung which leads to the emission of the gamma rays from the nuclei of atoms in excited states with a continuous energy distribution.

Gamma rays are characterised by the radionuclides present in the emission of the photon, hence the intensities of the emitted photon of gamma-radiation determine radionuclides in the sample.

The behaviours of gamma and x rays are in principle different from that of the alpha and beta rays. Alpha and beta lose energy by colliding with other particles, while γ – radiation gives off their energy in a single process because they do not have a charge.

For the absorption of gamma-rays, the equation below is valid:

$$I = I_0 e^{-\mu d}$$

Where;

I, is the Intensity of the photon

$\mathbf{I_0}$ is the Initial intensity of photon

μ is the attenuation coefficient

d is the distance travelled by the photon

The equation is also used to determine the shielding ability of some materials as an attempt to use those materials as radiation protection equipment.

Neutrons

Neutrons play an important role in nuclear fission with available fluxes that can be used in side reactions. Spontaneous fission of heavy nuclei produces neutrons which are unstable in free state. Because neutrons do

not have charges (electrically neutral), primary ionization by neutrons is negligible since their interactions with electrons is very small.

Internal Conversion (IC)

The interaction of orbital electrons with the nuclear field of unstable atoms results to an ejection of an electron from the atom as long as the energy is large enough to overcome the orbital energy. This process is called internal conversion. Internal conversion is distinct from Electron capture and beta-decay in the sense that it doesn't bring about neutron decay. It is usually experienced in atoms that are in an electromagnetically excited state. Information about electric multipole character of the nucleus and the binding energies of the electrons in the daughter atom can be obtained from the intensities of the internal conversion.

Electron Capture (EC)

Electron Capture also referred to as K-capture is the capture of an electron by the nuclei of a radionuclide thereby leading to an emission of neutrino. Just as in the case of positron-decay, the effect of Electron capture on an atom of a radionuclide is similar. The electron is captured from the K-shell of an atom and the resulting process will be the falling of a higher-level electron into the vacant k-shell through a release of an x-ray radiation. The other possibility is the Auger effect, where an outer electron is removed to balance the energy emitted by the captured electron.

$$^{7}_{4}Be + {}^{0}_{-1}e \rightarrow {}^{7}_{3}Li + {}^{0}_{0}v$$

Spontaneous fission

Massive nucleus such as ^{235}U break down or split into two smaller fragments with the emission of energy. The sum of the masses of the resulting fragments are usually less than the starting material and this is called Spontaneous fission. In 1940 K. Petrzak and G. Flerov found that ^{238}U in addition to alpha - decay also had a competing mode of radioactive decay termed spontaneous fission (Gregory 2013). Spontaneous fission can also be induced by bombarding the radionuclide with high energy neutrons leading to the formation of two different fragments of the initial starting material.

The result of spontaneous fission as mentioned, is two fission products with neutrons ejected from the nucleus. The neutrons from spontaneous fissions are however used in side reactions to induce other nuclear reactions mainly for energy production. Spontaneous fission is usually common in atoms with very large Z (atomic number) values.

Apart from uranium-235 that is naturally known to exhibit nuclear fission, other radioisotopes can be induced to fission by bombarding the atoms with high energy neutrons slowly. Examples include Plutonium-239, Thorium-232, and other isotopes of Uranium.

Uranium-235 is the most commonly known atom that naturally undergo fission when in contact with slow neutrons. Fast neutrons are difficult to capture, hence the best avenue for the fission of Uranium-235 is a slow neutron. The fission of uranium-235 and other nuclear fission products can yield over 200million times the energy of the neutron that triggered the fission reaction with an enormous release of energy.

Conclusion

Radioactive decay of different atoms has shown dramatic change in characters with increasing atomic number, particle mass and energy of emission. The alpha particle is emitted by larger atoms while in smaller atoms we experience beta radiation or electron capture. Interesting interactions of the nuclear field with electron

orbitals has also induced the emission of the zero charged gamma-photon or the x-ray which is known as the bremsstrahlung effect. The type of bremsstrahlung effect is characterized by its energy of emission and the mode of emission. The neutron which is of great importance in spontaneous fission is also a good source for nuclear energy since it is both important in nuclear side reactions and spontaneous fissions when the energy is big enough to disturb subatomic particles. This paper is aimed to summarize important terms used in radioactive decay and also as a of the requirement to satisfy the grading of the Introductory Nuclear Chemistry course at the University of Warsaw.

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